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Optimization Studies for
Integrated Solar Combined Cycle Systems

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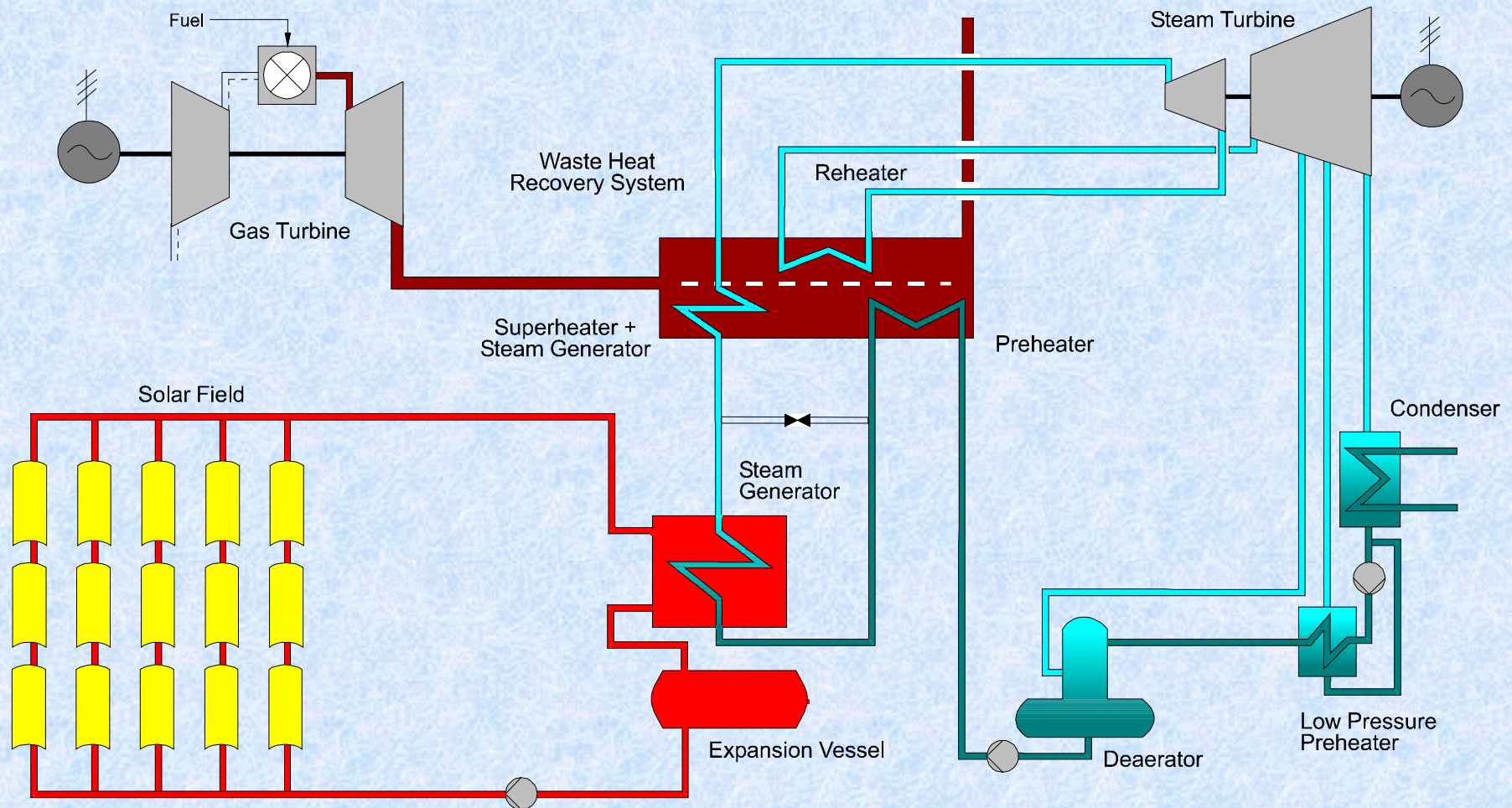Nexant Inc., A Bechtel Technology & Consulting Company

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Integrated Solar Combined Cycle System

Thermodynamic and Economic Benefits

- Incremental Rankine cycle efficiencies are 95 to 120 percent those of a solar-only plant, and up to 105 percent those of a combined cycle plant

- Daily steam turbine startup losses are eliminated

- Incremental Rankine cycle power plant costs are 25 to 75 percent those of a solar-only plant

Combined Cycle Plant

- 154 MWe General Electric PG7241(FA) gas turbine-generator (25 °C, 600 m), with dry, low NOx combustors and fueled by natural gas

- 3 pressure heat recovery steam generator: 100 bar and 565 °C; 28 bar and 565 °C; and 4 bar and 290 °C

- 90 MWe single reheat steam cycle

Annual Performance Model

- Combined cycle plant modeled with GateCycle®

- Brayton cycle: Electric power output and fuel use as functions of ambient temperature

- Rankine cycle: Electric power output as a function of ambient temperature and collector field thermal input

- Hourly direct normal radiation and ambient temperature file for Barstow, California

Annual Performance Model (Continued)

- Collector field output: Direct normal radiation; sun position; collector optical efficiency; receiver thermal efficiency; and piping thermal losses

- Hour by hour calculation of collector field output, Brayton cycle output, fuel use, and Rankine cycle output

- 8,760 hour per year operation

Solar Thermal Energy Use

- Low, intermediate, and high pressure saturated and superheated steam production, with steam returning to heat recovery steam generator

- Intermediate pressure superheated steam production, with steam returning to gas turbine combustor

- Oil-to-flue gas heat exchanger sections in heat recovery steam generator

Solar Thermal Energy Use (Continued)

- The most efficient use of solar energy is high pressure, saturated steam production

- Rankine cycle conditions are unchanged from those in conventional plants, yet solar thermal-to-electric conversion efficiencies are higher than in conventional plants

# Heat Transfer Diagram for Combined Cycle Plant
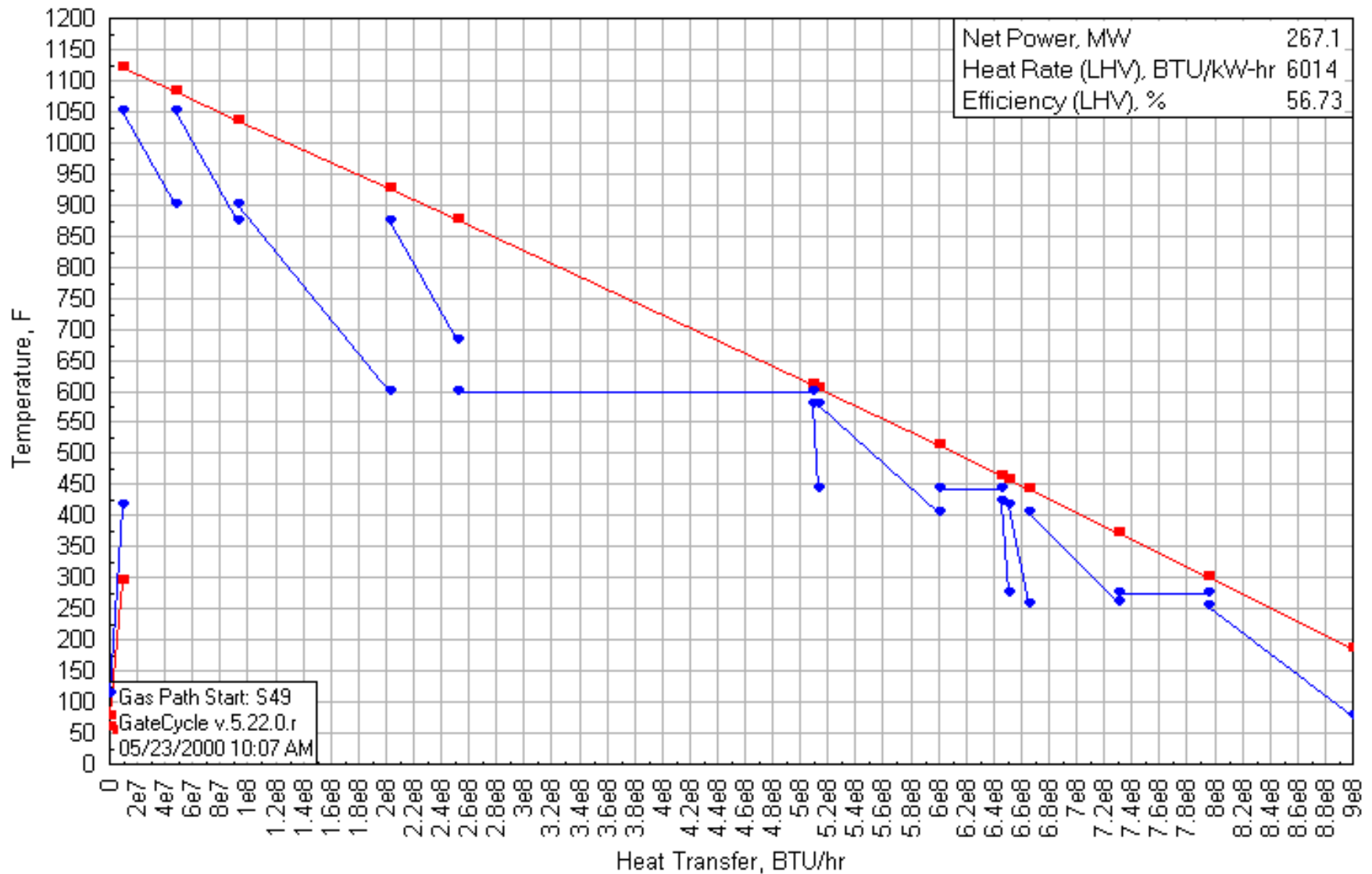
ISCCS with Small Solar Input
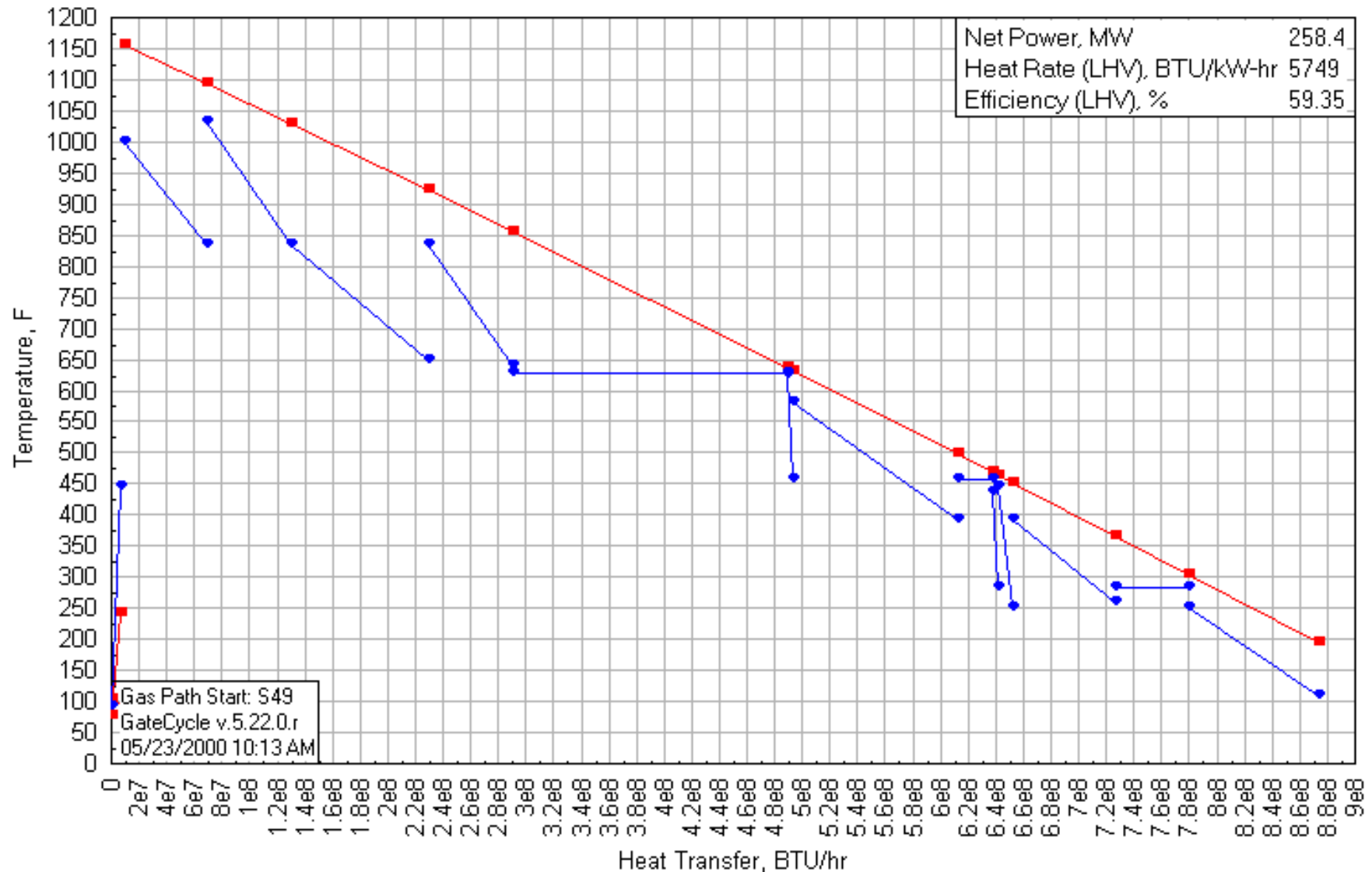
Thermodynamic Benefits

- Joule of energy at 500 °C performs more work than a Joule at 400 °C

- Largest Rankine cycle temperature differences occur in high pressure evaporator of the heat recovery steam generator

- Solar thermal input, if moderate, reduces average temperature difference between turbine exhaust gas and Rankine cycle working fluid

- Solar input improves conversion efficiency of (much larger) fossil input to Rankine cycle

ISCCS with Large Solar Input
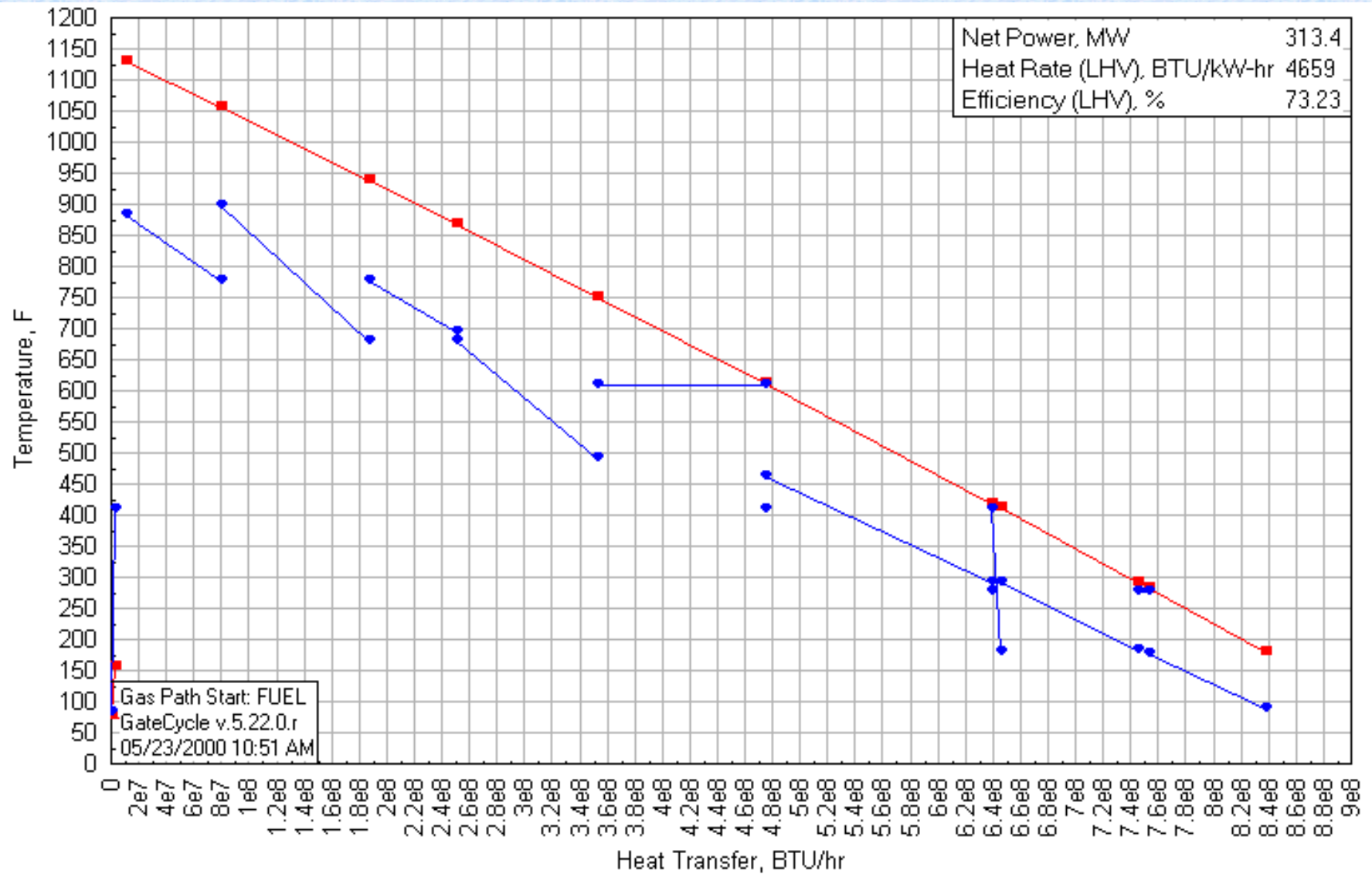
Inherent Limits

- Small solar input
  - Offsets primarily saturated steam production
  - Rankine cycle work = $\int \upsilon \, dp$
  - Steam turbine part load ΔP is 80 to 90 percent of full load ΔP, and evening efficiency penalty is small

- Large solar input
  - Offsets saturated steam production and feedwater preheating
  - Steam turbine part load ΔP is 50 to 75 percent of full load ΔP, and evening efficiency penalty is larger

Benefits and Limits
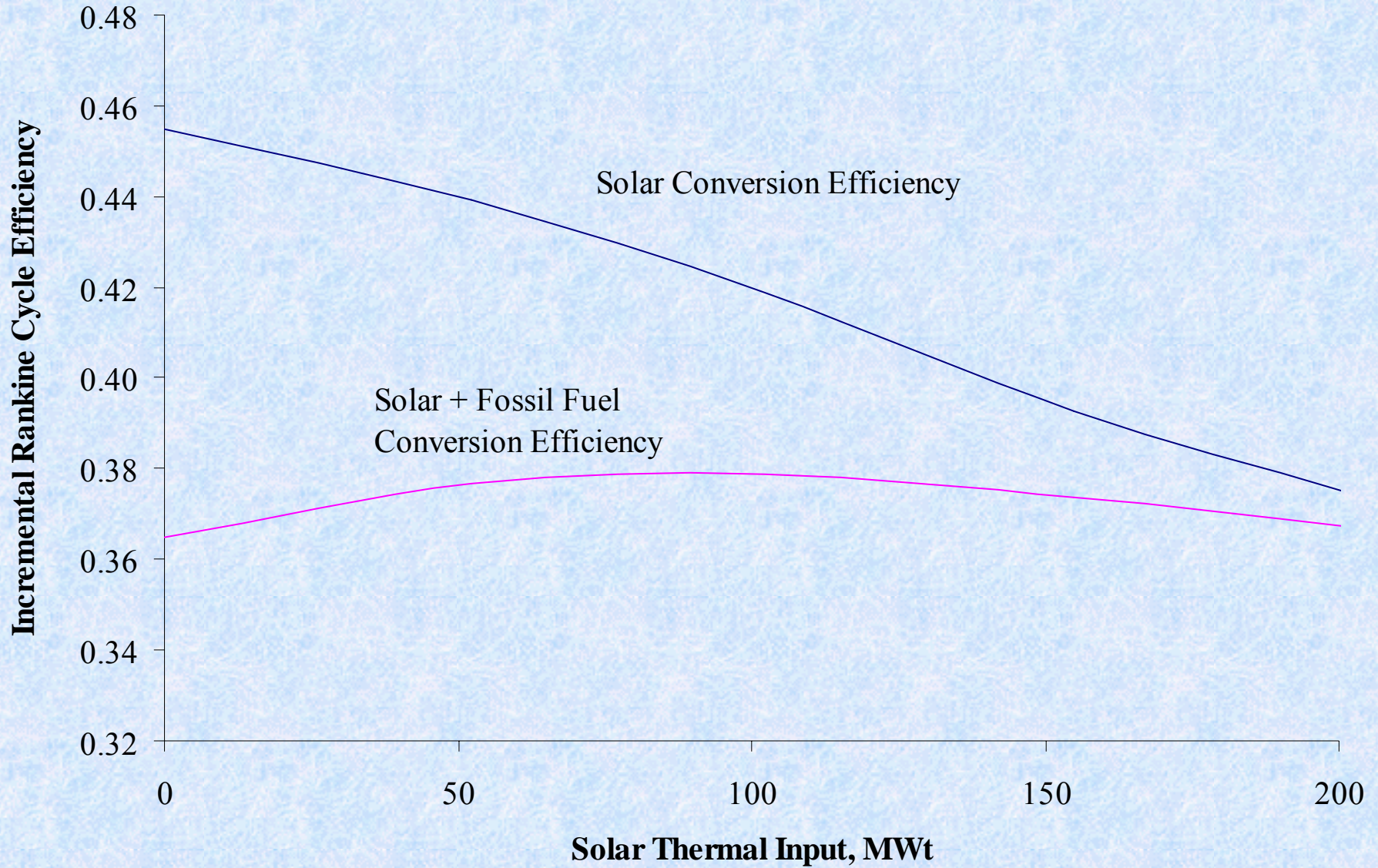
Live and Reheat Steam Conditions

- Steam flow rates are highest during solar operation; turbine operates at design pressure during the day, and at reduced pressures overnight

- Superheater and reheater can be sized for:
  - Solar operation, with attemperation required at night
  - Evening operation, with temperature decay during solar periods

Live and Reheat Steam Conditions

Heat Exchangers Sized for Solar Operation

	Live steam pressure, bar	Live steam temperature, °C
Solar Operation	125	565
Evening Operation	70 - 125	565

Heat Exchangers Sized for Evening Operation

	Live steam pressure, bar	Live steam temperature, °C
Solar Operation	125	450 - 565
Evening Operation	70 - 125	565

Live and Reheat Steam Conditions

- Heat exchangers sized for solar operation

  - Highest solar thermal-to-electric conversion efficiencies

  - Annual solar contributions up to 6 percent; limited by feedwater attemperation between first and second superheater stages

- Heat exchangers sized for evening operation

  - Less complex control system

  - Annual solar contributions up to 9 percent; limited by minimum allowable ratio of 0.4 for continuous live steam pressure to design pressure

Solar Contributions and Efficiencies

- 32 to 33 percent net solar thermal-to-electric conversion efficiencies for solar-only parabolic trough plants

- Integrated Plants
  - 40 to 42 percent net solar conversion efficiencies with annual solar contributions of 1 to 2 percent
  - 32 to 35 percent net efficiencies with solar contributions up 9 percent

Solar Contributions and Efficiencies

- Integrated Plants (Continued)

  - Unit capital and operating costs for the incremental Rankine cycle plant are lower than for the complete Rankine cycle plant in a solar-only facility

  - Economic annual solar contributions may be as large as 12 percent

Conclusions

- Incremental Rankine cycle efficiencies are higher than those in a solar-only plant, and can be higher than those in a combined cycle plant

- Incremental Rankine cycle power plant costs are 25 to 75 percent those of a solar-only plant

- Offers the lowest cost of solar electric energy among hybrid options